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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A COST-EFFECTIVENESS ANALYSIS OF ALTERNATIVE GUIDED MEDIA FOR THE BACKBONE CABLE PLANT PORTION OF THE BASE INFORMATION TRANSFER SYSTEM

by

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March 1991

Thesis Advisor: William Gates

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School

6b OFFICE SYMBOL (If applicable): AS

7a. NAME OF MONITORING ORGANIZATION: Naval Postgraduate School

6c. ADDRESS (City, State, and ZIP Code): Monterey, CA 93943-5000

7b. ADDRESS (City, State, and ZIP Code): Monterey, CA 93943-5000

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) A COST-EFFECTIVENESS ANALYSIS OF ALTERNATIVE GUIDED MEDIA FOR THE BACKBONE CABLE PLANT PORTION OF THE BASE INFORMATION TRANSFER SYSTEM

12. PERSONAL AUTHOR(S) SKELLY, Vernon M.

13a. TYPE OF REPORT: Master's Thesis

13b TIME COVERED FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day): 1991 March

15 PAGE COUNT: 68

16 SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the US Government.

17 COSATI CODES		
FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Cost-effectiveness; optical fiber; twisted-pair wire; Navy Base Information Transfer System (BITS)

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The Base Information Transfer System (BITS) and the Telephone Modernization Plan (TMP) will upgrade the backbone cable plant of the telephone system on Navy bases. Using a hypothetical Navy base and its existing twisted-pair wire network, this paper analyzes the unique costs of optical fiber and twisted-pair wire for four installation options: immediate installation of optical fiber; time-phased installation of optical fiber; time-phased installation of twisted-pair wire in trenches; and time-phased installation of twisted-pair wire in existing conduit. The cost analysis indicates that the lowest cost option is twisted-pair wire installed in conduit. However, the cost-effectiveness analysis concludes that time-phased installation of optical fiber is the best alternative due to its performance characteristics.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL: GATES, William

22b TELEPHONE (Include Area Code): 408-646-2754

22c OFFICE SYMBOL: EC/Ga

DD Form 1473, JUN 86 *Previous editions are obsolete* SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603 UNCLASSIFIED

Approved for public release; distribution is unlimited

A Cost-Effectiveness Analysis of Alternative Guided Media for the Backbone Cable Plant Portion of the Base Information Transfer System

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN TELECOMMUNICATIONS SYSTEMS MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
March 1991

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ABSTRACT

The Base Information Transfer System (BITS) and the Telephone Modernization Plan (TMP) will upgrade the backbone cable plant of the telephone system on Navy bases. Using a hypothetical Navy base and its existing twisted-pair wire network, this paper analyzes the unique costs of optical fiber and twisted-pair wire for four installation options: immediate installation of optical fiber; time-phased installation of optical fiber; time-phased installation of twisted-pair wire in trenches; and time-phased installation of twisted-pair wire in existing conduit. The cost analysis indicates that the lowest cost option is twisted-pair wire installed in conduit. However, the cost-effectiveness analysis concludes that time-phased installation of optical fiber is the best alternative due to its performance characteristics.

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I. INTRODUCTION

The purpose of this thesis is to explore the options available for the backbone cable plant portion of the Base Information Transfer System (BITS). The BITS is the successor to the telephone system that currently supports the administration of a Navy base. Before attempting to improve any communications system, the current system must be analyzed to determine its strengths and liabilities. After analyzing the existing system, a clear and concise picture of the desired communication system is needed. Finally, cost and technical specifications must be developed in order to compare alternative plans for the BITS backbone cable plant.

A. CURRENT COMMUNICATIONS SYSTEMS

As indicated in the Navy Data Communications Control Architecture (NDCCA) [Ref. 1:encl. 1, p. 3; Ref. 2:p. xi], existing base communications systems are reliable, mission-oriented, and adequately satisfy current needs. However, many are antiquated, costly, and use manual, error-prone methods. In addition, because individual organizations developed unique systems to satisfy their communication needs, the systems are incompatible. When interoperability becomes necessary, other systems are developed to translate from one unique system to another. This is all costly, inefficient, and can lead to bottlenecks in the transfer of critical decision/mission support data. It is also all too common.

B. FUTURE COMMUNICATIONS SYSTEMS

The desired communications system is an integrated communications system using the most cost-effective equipment. These systems must not only be interoperable within the Navy and the Department of Defense but also interoperable with the civilian world. Communications equipment manufacturers, driven by their customers demands, have made substantial progress towards standardization of protocols. Standardized protocols permit dissimilar communications equipment to "talk" to one another in a standard language.

Use of standardized protocols within the Navy will permit the procurement of the most cost-effective communications equipment with the assurance that it will be interoperable. Systems that were isolated will now be able to transfer critical decision/mission support data efficiently and effectively without the old, error-prone methods. This is the direction the Navy has chosen.

The Navy's desired end-state is specified in the Navy Data Communications Control Architecture (NDCCA). The NDCCA specifies the standard protocols to be used and offers guidance in other areas. It separates the Navy communication systems into three broad categories, of which the BITS is one. Other Navy programs, such as the Telephone Modernization Plan

(TMP), direct the updating of base telephone systems. The TMP implements certain aspects of the BITS program.

C. BACKBONE CABLE PLANT

As stated above, the purpose of this thesis is to explore the options available for the backbone cable plant portion of the BITS. The backbone cable plant is one element of the BITS. It must be capable of meeting the demanding requirements of the BITS, yet flexible enough to accommodate future demands. It must also be cost-effective throughout its useful life.

The basic requirement for the backbone cable plant is that it be able to transfer information, integrated voice and data, in a digital form from user to user [Ref. 2:pp. xi-xiii]. It must be reliable, secure, and not restrict the flow of data, either through limited capacity or the creation of errors in the digital bit stream. Many methods exist for the transmission of data, such as satellites, microwaves, cellular networks, or guided transmission media. The guided transmission media include twisted-pair wire, coaxial cable, and optical fiber. In most cases, Navy bases do not involve extensive areas of land. For this reason, this thesis will concentrate on the guided transmission media, but does not imply that other transmission methods are not effective.

In this thesis, Chapter II provides a background of the BITS. Physical transmission media characteristics will be presented in Chapter III. A cost analysis of different backbone cable plant options is performed in Chapter IV. Chapter V will present the conclusions of this thesis.

II. DEVELOPMENT OF THE BASE INFORMATION TRANSFER SYSTEM (BITS)

This chapter will present the development of the Navy's future communications. To correct the problems in the existing systems as described in the previous chapter, the Navy designed a plan that will guide the development and procurement of future communications systems. The umbrella instruction is the Navy Data Communications Program (OPNAVINST 2800.3), which includes the Navy Data Communications Control Architecture (NDCCA). Other Navy instructions support the NDCCA by addressing specific communications areas. It is important to understand that the Navy intends to take advantage of innovations in digital communications using commercial equipment to minimize developmental costs and maximize compatibility with other users.

A. NAVY DATA COMMUNICATIONS CONTROL ARCHITECTURE (NDCCA)

OPNAVINST 2800.3, dated 6 October 1988, was the culmination of several years of planning. The planning centered on how the Navy could exploit innovations in telecommunications to update its aging telecommunications systems. Innovations such as file transfer, electronic mail (E-mail), video teleconferencing, and interactive and record communication, will be needed to enhance the delivery of decision/mission support data. [Ref. 1:encl. 1 p. 2-3]

Current systems, which are not interoperable, are unable to provide these features at an economic cost or are unavailable to local users. This lack of interoperability slows critical information transfer and may prevent timely decisions.

Planners divided Navy communications into four parts; base, long-haul, ship-to-shore and shipboard. Within the NDCCA, three sub-architectures were identified to provide for the four parts of Navy communications. These sub-architectures are Base Information Transfer System (BITS), afloat and long-haul. Also identified were three control components that crossed over the three sub-architectures and interconnected them: security, protocol, and network management. Because of the scope of the NDCCA, target architectures were established for the current period, the interim period, and in the long range for each sub-architecture. Some of the target architectures are in current use while others are still on the drawing board.

1. Sub-Architectures

As described above, Navy communications were divided into three subarchitectures. BITS defines the structure of communications systems on Navy bases and stations. The afloat sub-architecture details shipboard communication for ship-to-ship and ship-to-shore, which includes both ships at sea and in port. The long-haul sub-architecture provides guidelines for inclusion of Navy communications in the Defense Communications System (DCS). [Ref. 2:p. 1-1] The BITS sub-architecture interfaces with the others through well-planned links. It will enable ships in port to connect directly into the long-haul sub-architecture, eliminating many of the previous time-consuming, error-prone communication methods.

2. Integration

Three control elements--protocols, security, and network management--were selected to integrate the three sub-architectures. Protocols are the rules for communication system operation and include such topics as types of service and administrative procedures. [Ref. 3:p. 243] Protocols currently are many and varied. It is necessary to standardize protocols in order to integrate the sub-architectures. The telecommunications industry is moving rapidly towards protocol standardization because of customers' demands for interoperability between different manufacturers' products. A key component to protocol standardization is the International Standards Organization Open Systems Interconnection (ISO OSI). The U.S. government had also experienced similar problems with multiple protocols and lack of interoperability of its various communications systems. In August 1990, it mandated the use of the Government Open Systems Interconnection Protocol (GOSIP), an OSI compatible model, for all subsequent development and procurement of communications systems. NDCCA directs the evolution of protocols toward the OSI model, specifically GOSIP.

Security is necessary to safeguard Navy communications from both physical intrusion, and a compromise of classified data. Security will be provided by both hardware and software. Hardware will include such devices as "Gateguard", "Blacker", and physically separate networks. Software will permit encryption of sensitive data, multiple level security, and provisions for "need to know" access. "The basic security requirements are: end-to-end protection, for message text, link encryption for traffic analysis protection and NSA provided crypto algorithms." [Ref. 1:encl. 1, p. 6-3] As indicated, software will be provided by the National Security Agency (NSA), but the hardware will be procured through commercial contracts.

Network management is the key to making existing systems interoperable. This function will be performed by the network management center (NMC). Network management is also a key component for efficient system operation, through the centralization of administration, operation and maintenance functions. It also provides a single point of contact to end-users and others. Security of the communications systems is monitored and enforced by the NMC. External interfaces to the Defense Switched Network (DSN) and the Defense Data Network are coordinated through the NMC.

Integrated Services Digital Network (ISDN) is a digital network that combines data and voice services over an integrated interface. The NDCCA target architecture is supposed to provide a "totally integrated ISDN capability both for shore-based and afloat information systems and information system users." [Ref. 1:encl. 1, p. 2-8] Currently, these services are provided by different access lines at a much greater expense. ISDN will provide digital connectivity and a wide variety of services, like E-mail, to the end-user. ISDN will be covered in depth at the end of this chapter.

B. TELEPHONE MODERNIZATION PLAN (TMP)

The Telephone Modernization Plan (NAVTELCOMINST 2061.1) of 21 January 1988, provides the plan and guidance for the modernization of the Navy's administrative telephone network. TMP supports BITS in many ways, especially through the upgrading of the base telephone switch and backbone cable plant.

1. Current Telephone Systems

Telephone systems on many Navy bases were designed and constructed using analog technology for the telephones, switches and the inside/outside cable plants. Many of the telephone installations are antiquated and maintenance intensive. [Ref. 4:p. 7] Twisted-pair wire was used extensively throughout both inside and outside cable plants. Twisted-pair wire was adequate during periods when most telephone traffic was voice. As data traffic requirements grow, the narrow bandwidth of twisted-pair wire limits transmission speed and the amount of data that can be transferred. Twisted-pair wire will be covered more extensively later in this and the next chapters.

2. Target Telephone Systems

The TMP provides for the replacement of all analog switches with digital fourth-generation Private Automatic Branch Exchanges (PABX). These PABXs will be capable of switching both voice and data, interfacing with the Defense Switched Network (DSN), and upgrading to ISDN capability. The Plan will also upgrade inside and outside cable plants. These upgraded cable plants will be sized to allow for 70% growth in base communications requirements. [Ref. 4:p. 5]

3. Switch Specifications

Switches will be digital, computer-operated PABXs. Most of the switches will have a capacity of several hundred or several thousand lines depending on the size of the base. Required switch specifications ensure compatibility with ISDN. End-users will be provided with two 64 Kilobit/second clear voice and data channels and one 16 Kilobit/second signaling channel. The switch must also be capable of interfacing with 1.544 Megabit/second T-1 digital groups. Common Channel Signaling System No. 7 (CCSS7) will provide the capability for the clear voice and data channels. Also required are terminal adapters for non-ISDN equipment, such as Personal Computers (PC), to adapt their data transfer protocols and transfer rates to the ISDN standards. [Ref. 4:encl. 3 p. 1]

Additional features that may be offered, depending upon the base's requirements, are: automatic message accounting, least cost routing, call blocking, station-to-station dialing, station and trunk hunting, queuing, dial transfer, hold, conference calling, call waiting indication, call forwarding, direct outward dialing, abbreviated dialing, multi-level precedence and pre-emption (MLPP), dial service assistance, DSN/AUTOVON interface, and hold indicator. [Ref. 4:encl. 3 pp. 2-4]

4. Additional Considerations

The type of switch selected for the base depends largely on the particular base requirements. Current ISDN switches use mainly proprietary protocols because the final ISDN protocols will not be available until at least 1992. This implies that switches selected must be compatible with the switch at the Local Exchange Carrier (LEC). This requirement will disappear after the final ISDN standards are approved and implemented by PABX manufacturers.

Another consideration is the physical transmission medium selected. The choice of guided transmission media is a choice between twisted-pair wire, coaxial cable, and optical fiber. The Chief of Naval Operations (CNO) has directed the consideration of optical fiber in all new cable installations where it is cost effective. [Ref. 5:p. 3-9] The use of optical fiber will mean selecting a PABX that is capable of terminating optical fiber, or capable of being upgraded to terminating optical fiber through additional interface equipment. Knowledge of the type of transmission media to be used must be obtained before selecting a switch.

As stated above, the requirement to provide for 70% growth in the backbone cable plant also means that the switch must allow for growth. It is beneficial to be able to upgrade the switch using modular components rather than a "forklift" upgrade of the whole switch.

C. BITS SUB-ARCHITECTURE

An objective of BITS, as a part of the NDCCA, is to standardize communications throughout the Navy. It is a plan that provides "a coherent communications planning structure at the base level that conforms to the general principles and guidelines promulgated by the NDCCA". [Ref. 2:p. 1-4]

1. Definition

"BITS is an integrated voice, data, image, message and video communications architecture for Navy bases for intrabase communications and support of ships at the pier." [Ref. 2:p. 1-3] As indicated in the NDCCA, the Navy suffers from incompatible systems that hamper the flow of decision/mission support information. On a typical base, LANs are not interconnected to enhance the flow of data except through low-speed modems (<9600 bits/second). Some bases lack interbase data communication facilities (DDN) for their LANs. The BITS is intended to integrate the disparate communication elements found on a Navy base and between Navy bases to speed the flow of critical data.

2. Topology

The basic topology of the BITS consists of a base switch complex meeting the requirements of the TMP, a backbone cable plant for integrated voice and data transmission, multiplexers and local area network (LAN) gateways for interfacing buildings and piers to the backbone, and a universal wiring scheme for the buildings on the base. "The base switch complex may comprise one or more of the following: DSN switch (circuit switch), packet switch, PABX and [Message Transfer Agent] MTA." [Ref. 2:p. 4-6] Similar to the NDCCA, the BITS target architecture is based on ISDN.

ISDN was originally designed to use twisted-pair wire for its transmission medium. However, ISDN can be provided using coaxial cable or optical fiber as well. In the backbone cable plant and the universal wiring scheme, any type of transmission media may be used. Since most bases are currently wired with copper twisted-pair wire, no upgrading is needed immediately unless it must comply with the requirements of the TMP.

3. Selection/Procurement

It is intended that BITS will utilize commercial off-the-shelf (COTS) equipment as much as possible, to reduce developmental costs and ensure interoperability of communications equipment. Because the base switch was dealt with under the TMP, we will deal exclusively with the transmission media in this section. Many criteria are involved in selecting the type of media to be used: bandwidth, repeater requirements, power requirements, multiplexers, connection devices, and the most important factor--cost.

Because coaxial cable is already more expensive, has a smaller bandwidth than optical fiber, and is more difficult to work with than either twisted-pair wire or optical fiber, it will be eliminated from consideration. [Ref. 6:p. 40] Basic characteristics of twisted-pair wire and optical fiber are discussed in Chapter III. However, other considerations beyond the basic comparisons are necessary. Twisted-pair wire has a bandwidth of several hundred kilohertz, while optical fiber has bandwidths of several hundred megahertz for multimode fiber and several gigahertz for single-mode fiber. This means that more twisted-pair wires are needed to transfer large amounts of information quickly, increasing the cost of twisted-pair wire systems. In this thesis, the more expensive single-mode fiber was selected in order to save future installation costs and position the base for increased future data transmission demands.

Repeater requirements do not become an issue except at very large bases. Digital twisted-pair wires require a repeater at least every mile. The cost of these repeaters is already low due to wide-spread usage. Optical fiber systems typically require a repeater every 40 miles. Power requirements present a much larger issue. Because optical fiber is a dielectric medium (i.e., it does not conduct electricity), power must be provided by a separate network. Twisted-pair wire is able to carry along power in addition to information, thus providing power to necessary components in the system. In the example of our hypothetical base, no repeaters are required and power can be provided by the electronics at either end of the optical fiber, end-user and PABX.

The electronics, optical multiplexers, and optical modems required in an optical fiber network are necessarily more complex and expensive than in a twisted-pair wire network. Some costs may be saved by using light emitting diodes (LED) and PIN photodetectors, which are less expensive, but less capable, than injection laser diodes (ILD) and avalanche photodetectors (APD). There are many trade-offs between the LED and ILD systems, which will not be covered in this thesis. A benefit to optical fiber systems is that the electronics may be upgraded to increase the data transfer rate without changing the optical fiber network.

Connections or splices involving optical fiber are much more demanding than twisted-pair wire. Optical fibers must be nearly perfectly aligned when coupled together in order to transfer a large percentage of the photons travelling through them. Improper alignment causes a loss of photons or optical power. Manufacturers are developing automatic splicing machines to make optical fibers more cost-effective. Twisted-pair wire connections are very simple to make and do not result in significant power losses.

Throughout the 1980's, long distance companies aggressively installed optical fiber in their networks. Their demand for optical fiber provided the economies of scale needed to dramatically lower cost. The cost of optical fiber is now less than coaxial cable and is rapidly approaching the cost of twisted-pair wire. The cost comparison is commonly made in terms of the break-even distance--the distance at which the costs of an optical fiber system are equal to the costs of a twisted-pair wire system. Within the break-even distance it is more cost-effective to use twisted-pair wire and beyond the break-even distance it is more cost-effective to use optical fiber. In the mid-1980's, the break-even distance was approximately 2.5 miles. Today, the break-even distance is approximately 1.5 miles. [Ref. 7: p. 104] As LECs install fiber in the local loop, the cost of optical fiber and the break-even distance will continue to drop.

D. INTERNATIONAL STANDARDS ORGANIZATION OPEN SYSTEMS INTERCONNECT (ISO OSI)/INTEGRATED SERVICES DIGITAL NETWORK (ISDN)

1. ISO OSI

In the past, vendor-unique protocols have resulted in end-users purchasing expensive and complex protocol converters to enable dissimilar computers to "talk" to one another. The

ISO together with other standards organizations (EIA, CCITT, ANSI, etc.), developed the OSI model to provide a common standard and reduce the effects of vendor-specific protocols.

The stated purpose of the OSI Reference Model (OSI RM) is to:

- Establish a common basis for standards development
- Qualify products as open by their use of these standards.
- Provide a common reference for standards. [Ref. 8:p. 15]

It also accomplishes the following:

- Provides standards for communication between systems.
- Removes any technical impediment to communication between systems.
- Eliminates the need to describe the internal operation of a single system.
- Defines the points of interconnection for the exchange of information between systems.
- Narrows the options in order to increase the ability to communicate between systems without expensive conversions and translations. [Ref. 8:p. 16]

OSI is constructed of seven interdependent layers where each layer uses the services of layers below to perform services for layers above. The services from bottom to top are a) physical layer, b) data link layer, c) network layer, d) transport layer, e) session layer, f) presentation layer and g) application layer. These layers are the foundation of current and future protocols and are necessary for dissimilar data communications equipment to interoperate. The functions of these layers will not be covered in this thesis. The interested reader should review a data communications textbook or journal for further explanation.

2. ISDN

ISDN technologies will provide digital connectivity worldwide to end-users for voice, data, text, graphics, music, and video. This connectivity will be initially provided over common twisted-pair wiring and a standard interface plug for narrowband ISDN. Later, as twisted-pair wire is replaced by coaxial cable or optical fiber, broadband ISDN will be made available. By initially using twisted-pair wire, ISDN ensured its success in the near future, but retained the ability to grow.

ISDN is centered on three main areas:

- The standardization of services offered to subscribers in order to foster international compatibility.
- The standardization of user-to-network interfaces in order to foster independent terminal equipment and network equipment development.
- The standardization of network capabilities in order to foster user-to-network and network-to-network communications. [Ref. 8:p. 743]

ISDN uses bearer services and teleservices to provide the end-user with full support in all seven layers of the OSI model. Bearer services provide support for the lowest three layers. Bearer services deal mainly with the transmission of data and remain invisible to the end-user. Teleservices provide support through all seven layers, generally using the bearer services. Teleservices involve the applications the end-user wishes to use, i.e., E-mail.

There are two basic levels of ISDN services. These differ by the quantity of data that can be transmitted. The two levels are:

- Basic rate - Two 64 Kilobits/sec (Kbps) data channels (B) with one 16 Kbps control signal channel (D). The channels are created through the use of time division multiplexing (TDM). The B channel can be further multiplexed into subchannels of 8, 16 or 32 Kbps. [Ref. 8:p. 746]

- Primary rate - 23 B channels and one D channel for a total of 1.544 Megabits/sec (Mbps). This is the equivalent of a T-1 digital line.

As mentioned above, the ISDN standards are yet to be finalized by the CCITT. The final version is expected in 1992. However, manufacturers, in an attempt to meet the expected market demand, have developed equipment based on the completed portions and their best guess about the incomplete portions of the standards. This has led to many incompatible proprietary standards. Upon completion of the standards, the software should be updated and the desired compatibility achieved.

ISDN will provide the integrated voice and data channels necessary for rapid transfer of decision/mission support data. New services and improved old services will be offered to the Navy. Security devices and environmental monitoring devices, such as fire and flooding detectors, will be able to transmit their data over the D channel instead of a separate network. E-mail, which is already common in the civilian world, will enable greater contact among various parts of the Navy. This may increase the traffic demand more than anticipated, reducing message traffic. Message traffic from bases and especially ships in port may be sent directly into the DDN, bypassing the naval telecommunications centers (NTCC). Video teleconferencing will permit meetings between widely separated groups, which may enhance the decision-making process and possibly save money.

Use of single mode fibers with ILDs/APDs will permit early installation of broadband ISDN (BISDN). This will permit the end-user to have several hundred megabits/second capacity. BISDN will permit separate high capacity networks to be eliminated. Possible uses in the Navy would be computer-aided design/manufacturing (CAD/CAM), high definition television (HDTV), computer aided logistics (CALS), and centralized technical libraries.

III. TRANSMISSION MEDIA

This chapter will present basic information about the physical transmission media to be considered in this thesis. The system requirements, both current and future, must be established to determine if a medium is technically capable of meeting these requirements within budgetary constraints. When viewed in terms of system requirements, either twisted-pair wire or optical fiber will be satisfactory in most, if not all, categories. Other media, such as microwave or cellular networks, may be capable of fulfilling system requirements, but will not be considered. Coaxial cable will not be considered for the reasons outlined in Chapter II.

The criterion for selecting the best transmission medium has many different aspects, depending on the viewer's perspective. For the system user, the media should be transparent; for the engineer, it should satisfy the system requirements; and for management, it should be the most cost-effective solution. Consider the two transmission media: twisted-pair wire and optical fiber. If the system requirements are not excessively demanding and system costs are within the budget, either of the two media would be satisfactory. Each has its advantages and disadvantages as will be discussed. Before reviewing the characteristics of these two guided media, the differences between digital and analog transmission will be presented.

A. ANALOG/DIGITAL TRANSMISSION

Digital transmission of data and voice, which BITS will require, differs in many respects from analog transmission. Analog transmission uses continuously varying frequency, amplitude (voltage or current) or phase as the method of signaling. Digital transmission uses discrete levels of frequency, amplitude, or phase as the method of signaling. Both methods are mature, but analog is older. Digital transmission and switching is more efficient in terms of speed, size, power requirements, and reliability. Because of these efficiencies, transmission networks are rapidly being converted from analog to digital. However, the cost of installing new digital switching equipment and transmission lines is high. Local telephone companies are slowly phasing in digital networks where analog equipment is due for replacement or their customers need higher capacity service.

Capacity of the digital equipment and lines is determined in bits of information transmitted per second. Certain bit rates have been established as standards in North America. The fundamental bit rate is 64 kilobits/second and is labeled as DS-0 (Digital Signal level 0). The others are multiples of DS-0 and are as follows [Ref 9:p. 59];

DS	Bit Rate
DS0	64 kilobits/second

DS1	1.544 megabits/second (also known as T-1)
DS1C	3.152 megabits/second
DS2	6.312 megabits/second
DS3	44.736 megabits/second
DS4E	139.264 megabits/second
DS4	274.176 megabits/second

B. TWISTED-PAIR WIRE

Twisted-pair wire is the oldest, least expensive and least capable of the transmission media. It is most commonly found in the local loop of telephone networks and also in some local area networks. Twisted-pair wire derives its name because two wires are twisted together to reduce mutual interference or crosstalk. It also cancels out much of the external noise in the wire. Crosstalk is interference from another pair of wires in the cable bundle that allows conversation or noise to bleed from one circuit to another. Twisted-pair wire is considered narrowband, due to its limited frequency range of approximately 268 Kilohertz. [Ref. 10:p. 164] Higher frequencies are not used because twisted-pair wire radiates energy in excess of Federal Communications Commission (FCC) requirements and crosstalk increases with the square of frequency. Data transmission rate over twisted-pair wire, which is a function of bandwidth, is inversely proportional to the length of the wire.

1. Balanced/Unbalanced Twisted Pair Wire

Twisted-pair wire can be either balanced or unbalanced. A balanced line carries current on both wires in opposite directions. An unbalanced line carries current in only one wire, while the other wire acts as a ground. Balanced lines are more resistant to disturbances or stray currents, and thus cause fewer problems to transmission.

2. Wire Sizes

Wire gauge or diameter is determined by the American Wire Gauge (AWG) system. Smaller diameter wires, which are higher gauge, have greater resistance to current. The higher the gauge of wire and the longer the line, the higher the path resistance. High path resistance produces more signal loss and lower bit transfer rates.

> Local telephone loops are usually 22 to 26 gauge, with the bulk of telephone twisted pairs (TTP) using 24 gauge. Long-distance lines typically employ 19 gauge wires. [Ref. 8:pp. 121-2]

3. Shielded/Unshielded Pairs

Unshielded twisted pairs (UTP) are the most common twisted-pair wire. They lack a metallic sheathing or braid and suffer from greater environmental crosstalk and interference. UTP is adequate for short distances and lower frequencies. Shielded twisted pairs (STP) have a metallic sheath that lowers interference and crosstalk.

> Several analyses reveal that a shielded pair system improves resistance to crosstalk and noise by a factor of 1000 or more. Attenuation of TTP is about 2.3 times more severe than shielded pairs. [Ref. 8:p. 123]

STP, however, is more expensive than UTP.

4. Transmission Losses

Many problems arise when using metal wires for transmission. Envelope delay distortion is caused by electromagnetic waves of different frequencies travelling at varying speeds through a wire. Since the waves originate at the same location, the waves that travel at a slower speed arrive later. This causes the information contained by the wave to be distorted or "smeared" out in time. Higher frequencies suffer heavily from distortion. Experiments showed that this was caused by the capacitance in a wire. Loading coils were introduced in early voice circuits to balance the capacitance and reduce the distortion.

> As good as loaded circuits are for voice, they are poor for data transmission. While loading improves the loss vs. frequency characteristics, it causes severe phase delay problems since the phase of the higher frequencies is much more shifted on loaded facilities than it is on non-loaded facilities. [Ref. 9:p. 20]

The narrow bandwidth of twisted-pair wire presents problems to digital transmission due to the attenuation and distortion caused by the nature of the copper wires. Precise transmission of digital data at economical transmission rates requires large bandwidth so the pulse train of ones and zeros can be received with little or no distortion.

T-1 systems were originally developed to carry digital data on twisted-pair wire. Because a pair of wires is required to carry digital data in each direction, the possibility of crosstalk is increased. Improvements in UTP, such as tighter winding, have reduced crosstalk. "Twisted pairs, when suitably conditioned and with repeaters spaced closely enough could be used to carry bit rates up to DS2 easily, but it just isn't practical." [Ref. 9:p. 61]

5. Transmission

Transmission over twisted-pair wires may use only two wires, but two two-wire pairs are more common. The use of four wires permits full-duplex or two-way conversations with other benefits, such as improved balancing through the use of balancing circuits. Two-wire pairs are used in local loops, while four wires are used in long distance lines. Many twisted-pair wires are normally bundled together into cables for ease in handling.

Twisted-pair wire was initially developed and used for analog transmission of telephone conversations. As computer technology progressed, the need to share data and computer resources required transmission of data over networks. Since computers deal with digital data, ones and zeros, and telephone conversations deal with continuously varying frequencies, serious deficiencies were uncovered. Digital data can be converted via a modem to analog and transmitted over common telephone lines, but only at extremely low data rates.

C. OPTICAL FIBER

Initial experiments with fiber optics were first conducted in the early 1960's. However, fiber optics remained experimental until the early 1970's. Since that time, there have been significant advances in both fiber technology and the supporting electronics.

Although fiber optics enjoy many advantages over twisted-pair wire cable, disadvantages remain. The advantages of fiber optic systems include [Ref. 11:pp. 8-9]:

- Larger bandwidth and small loss
- Smaller size and weight
- Lower material cost
- Lower system cost per channel-km
- Higher system channel capacity
- Electrical isolation of input and output of data paths
- Immunity to high temperature within reasonable limits
- Almost complete immunity to electromagnetic interference (EMI)
- Almost complete freedom from signal leakage and crosstalk
- Larger distance between repeaters
- Almost complete security against detection or interception by unfriendly forces
- Almost complete security from electromagnetic pulse (EMP) damage.

The drawbacks are:

- Need for more precise control of production parameters to obtain near-ideal fiber dimensions and index profiles

- Difficulty of joining individual fiber segments

- Limited lifetime of light sources and associated system reliability

- Need for fiber protection in order to allow for rough installation and maintenance treatment

- Need for additional equipment to convert electronic signals into optical signals.

As a minimum, a fiber optic system includes an optical transmitter, a fiber optic cable and an optical receiver. Each component has many additional subcomponents. The optical transmitter includes a source, such as an injection laser diode (ILD) or light emitting diode (LED), and a method of modulating the signal. The fiber optic cable includes segments of cable joined by splices or connectors, repeaters that process the received signal to enhance its quality and amplify it, multiplexers to combine several signals into one composite signal and coupling devices to combine several inputs of different wavelengths into one signal or decompose a signal into signals of different wavelengths. The optical receiver includes a detector, such as a p-i-n detector or an avalanche photodiode (APD), and a preamplifier.

1. Construction

Optical fiber includes a central silica glass core, normally less than 125 microns in diameter. Cladding (silica glass or plastic with a lower refractive index) provides support to the core and contains the field produced by the propagating light. The cladding is surrounded by additional layers, called jackets, which provide strength and protection from the environmental elements. The jackets are normally made of non-metallic yarn (Kevlar), steel, and/or plastic.

2. Index of Refraction

Index of refraction, radius, and fiber length are key variables in characterizing optical fiber. The index of refraction is a property of the material in the optical fiber. In optical fiber, a ray of light will travel at a speed, less than the speed of light, which is a function of the index of refraction and the wavelength, also called a mode. There are two types of optical fiber in relation to the index of refraction of the core.

The step-index fiber core has a uniform index of refraction. A step-index fiber will support many propagating modes, unless it has a very small diameter, in which case it will only support one mode. Since the step-index fiber will support many modes that will propagate at different speeds, this will tend to produce large signal distortion which is the main disadvantage of this type of fiber. This disadvantage is eliminated by reducing the diameter so that only one mode will propagate.

The graded index optical fiber has a core that has a varying index of refraction. The index of refraction decreases with increasing radius, generally in a parabolic shape. Using the graded index optical fiber, rays of light are refracted back toward the fiber axis. The rays of light propagating at different speeds travel equal-length optical paths and arrive at the receiver simultaneously.

3. Losses

Power losses due to the optical fiber material are due to two different effects. As a ray of light propagates along the fiber, it experiences attenuation and delay distortion. Attenuation corresponds to a decay in the power level due to the conversion of propagation power into heat and the scattering of propagating power from the fiber. Delay distortion corresponds to "smearing out" in time of the optical signal as it propagates. The optical wave carrying the information is composed of different frequencies, each travelling at a different velocity. Because each frequency in the wave travels at a different velocity and travels an identical path, the lower frequencies arrive later, causing the deterioration in the waveform. After some distance of propagation, the effects of attenuation and delay distortion will accumulate to the point where the ability to extract the digital information from the modulated optical signal is jeopardized.

4. Single- and Multi-mode Fiber

Other descriptions of optical fiber relate to core size. Core size is related to the wavelengths of light propagated in the fiber. There are two types of optical fiber in relation to core size, single-mode and multi-mode.

An optical fiber with a small core, typically 5 microns, is called a single-mode optical fiber. A single-mode fiber transmits only one wavelength and thus does not suffer from delay dispersion. The advantage of the single-mode fiber is the extremely wide bandwidth, approximately 10-50 gigahertz. [Ref. 11:p. 95] The disadvantages of single-mode fiber are the difficulty of coupling the source to the fiber and the containment of the power within the fiber.

An optical fiber with a large core, typically 50-62.5 microns, is called a multi-mode optical fiber. Multi-mode fibers support many propagating modes and suffer from attenuation and delay dispersion. Because multi-mode is subject to both attenuation and delay dispersion, its bandwidth is limited to approximately 100-300 megahertz. [Ref. 11:p. 95] Multi-mode fibers are used more frequently because the bandwidth is usually more than adequate and multi-mode fibers are easier to couple.

5. Cabling

To protect the delicate fiber from damage during handling and splicing and damage from environmental factors, the fiber is placed in a cable. Small flaws (cracks) in the surface of the fiber will eventually lead to deterioration of the fiber. The major factors in this deterioration are tensile stress or strain and humidity.

There are many layers external to the core and cladding to protect them from the environment. Layers of steel or non-metallic yarns (i.e., Kevlar) are added to protect the fibers from excessive tensile stress. This distributes the tensile stress--developed during installation or as a result of aerial installation over a larger area--and keeps it within acceptable limits. Other layers protect the fibers from crushing pressures. Typical methods are stranded steel wires or metallic tubes, and/or recessing the fibers in various cushioning layers. By engineering the layers, cable stiffness is produced to protect the fibers from excessive bending strain and accidental kinking. Outer layers of plastic are added as necessary to protect the fibers from the various environmental elements such as moisture, corrosion, heat and pests.

IV. ANALYSIS OF NETWORK

This chapter specifies the BITS backbone cable plant options to be considered in this thesis and performs a cost analysis for each option. The cost analysis will cover a twenty year period and will focus on the cable plant itself and items that are unique to each option (i.e., fiber optic transceivers). Common components will not be included. Finally, the two lowest cost options will be analyzed for effectiveness.

A. ASSUMPTIONS

1. Base

The cost analysis is based on a *fictitious* Navy base (see Figure 1 and Table I)--a composite of four California Navy bases with regard to size and number of piers. Standard functions, such as base and staff headquarters and a school complex, and a variety of buildings are included in the base. Telephone traffic requirements are established for each building. Other services, such as data and video transmission, are combined into the telephone traffic when establishing the required number of lines for each building.

2. Existing Backbone Cable Plant

It is assumed that the base has an existing twisted-pair network laid out in a trunk and feeder system that runs parallel to the streets. The existing system contains both

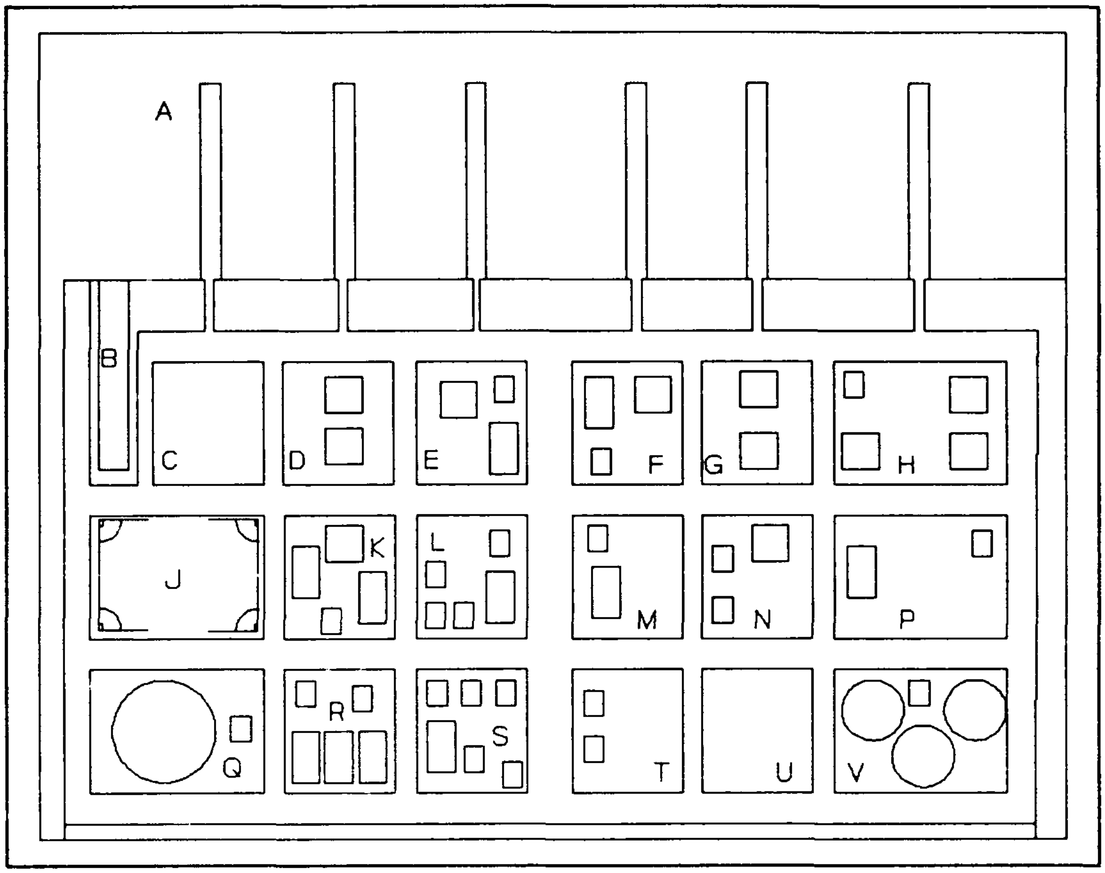

Figure 1 - Hypothetical Base Map

in-service lines and spares, which comprise five percent of the network. Trunks and feeders are laid in conduit while the building drop cables are laid in trenches. The capacity of the conduit for additional cable is a key point in the analysis. The capacity of the conduit will be discussed in the backbone cable plant options. Twisted-pair wire has a normal lifespan of 20-40 years, but it is subject to deterioration from environmental factors, such as rodents and chemical spills, and damage from construction projects. [Ref. 11:p. 8] During the twenty year period of the cost analysis,

Table I - Hypothetical Base Map Key

A	Piers
B	Dry Dock
C	Open Area
D	Maintenance Shops
E	Staff Bldg, Maint. Center and Shop
F	Base HQ, Admin., Maint. Shop
G	Maint. Shop
H	Supply Center/Whse
J	Softball Fields
K	School Comlex
L	Officer Club/Qtrs, Laundry, Medical, Fire Dept.
M	NTCC, NMC/Telephone Exchange
N	Public Works, Service Station, Hobby Shop
P	Power Plant, Sewage Pumping Station
Q	Water Storage/Pumping
R	Gym, BEQs, Mess Hall
S	Commissary, Exchange, CPO Club/Qtrs, Theatre Bowling, Security
T	Chapel, Family Service Center
U	Open Area
V	Fuel Storage/Pumping

the existing copper network must be replaced because of lifespan limitations.

As specified in Telephone Modernization Plan (TMP), the network must allow for a growth factor of 70%. The Chief of Naval Operations has further directed that all new projects consider optical fiber networks when they are cost-effective. For optical fiber to be cost-effective, there must be applications requiring its large bandwidth. It has been assumed that such applications will exist with the installation of a video conferencing center and interconnection of high speed local area networks (LAN) on the base and between local bases. Other large bandwidth applications may arise in the future. The replacement network options allow for a minimum growth factor of 70%.

In annual terms, five percent of the existing copper network must be replaced each year and three and one-half percent must be added each year for growth. After installing ISDN equipment, approximately one-half of the existing telephone lines would no longer be needed as one telephone line can service two previously separate telephones. It is assumed that these lines would act as spares, delaying the replacement of that section of twisted-pair wire. The number of spare lines available, used at eight and one-half percent per year (five percent replacement and three and one-half percent growth), would permit the delay of installation of a new backbone cable plant until year seven.

3. Costs

Additional assumptions are made regarding component costs, inflation rates, and real rates of growth or decline in component costs. A six percent inflation rate is assumed throughout the analysis. A range of real discount rates from six percent to 14% are used to calculate the net present value and indicate the opportunity cost of each option. Each component's cost (see Figure 2) is adjusted for inflation and price growth or decline on an annual basis and then discounted to present values over the range of discount rates.

Electronic component costs and optical fiber costs are assumed to decrease by four percent per year. Twisted-pair wire costs and labor related activities such as maintenance and installation are assumed to increase by six percent per year. Maintenance costs for twisted-pair wire are assumed to be ten percent of the price of twisted-pair wire. Optical

$$i := 1 \,..\, 20 \qquad \text{index for years one to 20}$$

$$cost_{component} := 25 \qquad \text{hypothetical cost for a component}$$

$$cost_{component_i} := \left[\frac{price_{growth.rate}}{inflation_{rate} + discount_{rate}} \right]^{i} \cdot cost_{component}$$

Figure 2 - Component Cost Function

fiber maintenance costs range from ten percent to 20% higher than twisted-pair wire maintenance costs. [Ref. 12:p. 21] Other costs have been drawn from various sources (see Table II).

B. BACKBONE CABLE PLANT OPTIONS

Four backbone cable plant options are considered in this thesis:

1) immediate replacement of the existing copper network with optical fiber,

2) optical fiber that is phased in over the twenty year period,

Table II - Summary of Component Costs

ITEM	COST	REFERENCE
128 channel fiber optic multiplexer	10,000	Ref 13, pg 56
32 channel fiber optic multiplexer	2,200	Ref 13, pg 56
8 channel fiber optic multiplexer	1200	Assumed
fiber optic transceiver (1300nm)	300-800	Ref 13, pg 56
PVC copper cable	.08-.12/ft	Ref 14, pg 44
duplex fiber optic cable	0.26/ft	Optical Cable Corp.
48-fiber cable	7.14/ft	Optical Cable Corp.
84-fiber cable	11.88	Optical Cable Corp.
120-fiber cable	15.72	Optical Cable Corp.
buried terminal 6 ports	40	Assumed
buried terminal 12 ports	50	Assumed
fiber optic installation in existing conduit	2.75/ft	Ref 15, Atch D-II-3
fiber optic installation in trench in earth	25/ft	Ref 15, Atch D-II-3

3) a replacement copper network that is phased in and can not be installed in the existing conduit and so is installed in a trench, and

4) a replacement copper network that is phased in and installed in the existing conduit.

In all cases, continuous service must be provided. Because of optical fiber cable's small diameter, it is assumed that the optical fiber cable would be placed in the conduit. The phase-in schedule will be the same for both optical fiber and twisted-pair wire. The time-phased installation allows for the spare cables resulting from the installation of the ISDN PABX to be used before replacement starts.

All options use a hierarchical star topology, which start at a central location, the PABX, and have several layers of distribution, i.e., trunks, feeders and drop cables. Lower levels of distribution branch out from the higher levels. A two-layer star was used in the optical fiber systems (see Figure 3) and a three-layer star in the copper systems (see Figure 4). Drop cables to the buildings, which form the lowest level of the star are not shown in the figures.

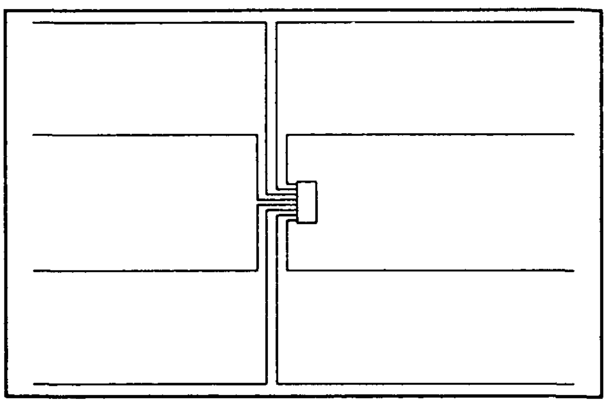

Figure 3 - Fiber Optic Distribution

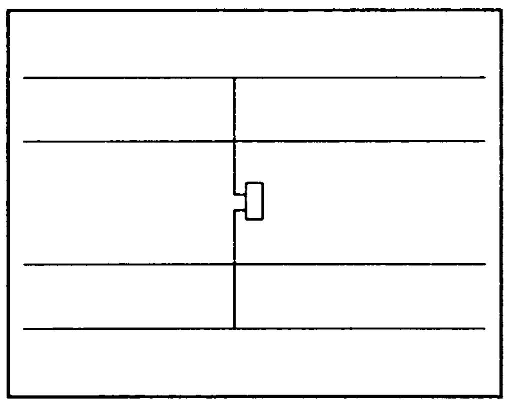

Figure 4 - Twisted-Pair Distribution

1. Optical Fiber

In the optical fiber systems, a multi-fiber breakout cable is installed from the PABX to buried distribution terminals along a distribution route. A smaller cable is removed from the larger distribution cable and terminated in the buried terminal. Duplex fiber cables are installed from the buried terminal to each of the nearby buildings. Duplex fibers are used to send and receive information between the user and the PABX. Inside the building the duplex fiber cable is connected to a multiplexer, which concentrates the building's telephone traffic into one line. The multiplexer has a fiber optic transceiver to convert the electronic signals into optical signals for transmission over the optical fiber. A multiplexer at the PABX converts the optical signals back into electronic signals for switching inside the PABX. In cases where there is only one telephone at a site, such as a guard shack, a fiber optic transceiver alone is used. Extra cable will be installed to permit additional fibers to be installed into new or existing buildings or to permit quick replacement of damaged fibers.

2. Twisted-Pair Wire

The twisted-pair wire systems use a more traditional network design of trunk cables, feeder cables and drop cables. Trunk cables are connected to the PABX and carry traffic from feeder cables. Feeder cables are spliced to drop cables inside smaller terminal boxes. Drop cables are connected to multiplexers in the buildings. Transceivers are not required because the entire system uses electronic signaling.

3. Option One

Option one, the immediate installation of optical fiber, is performed in year one. Cable, electronic components and terminal boxes are purchased at year one prices. Distribution cables are installed in conduit and the duplex fiber cables are installed in trenches. Finally, maintenance costs for the remaining 19 years are discounted to present values and summed.

4. Option Two

In option two, the time-phased installation of optical fiber, optical fiber is installed route by route. The largest routes, which include the piers and most staff buildings, are replaced first to serve the largest number of users. Installation begins in year six and continues every following year through year 13. Procurement and installation begins the year prior to actual use to allow sufficient lead time and to prevent interruptions in service during the transition. Cable, electronic components and terminal boxes for the route to be replaced are purchased in the year used. Distribution cables are installed in conduit and the duplex fiber cables are installed in trenches, as in option one. Maintenance costs for the copper network for the first six years are discounted to present values and summed. In following years, maintenance costs for the copper portions of the network are reduced by the amount of copper replaced by optical fiber, then discounted to present values and summed over the remaining 20 years. Maintenance costs for the optical fiber are discounted and summed over the remainder of the 20 year period.

5. Options Three and Four

Options three and four, the time-phased replacement by twisted-pair wire, differ only in the matter of installing the cable in the existing trench (option three) or in a conduit (option four). Replacement is performed by trunk and feeder sections. The most heavily used trunk is replaced first, followed by its feeder cables. The other trunk and its feeder cables are subsequently replaced. Installation begins in year six and continues every following year through year 15. Procurement and installation begins the year prior to actual use to allow sufficient lead time and to prevent interruptions in service during the transition. Cable is purchased in the year used. Installation costs depend on the option selected. The replacement system has a larger number of cables to satisfy the growth requirement. Maintenance costs for the existing network are discounted to present values and summed for the 20 years. As new cable is added, maintenance costs for the incremental amounts of cable are summed over the remainder of the twenty year period.

C. COST ANALYSIS

1. Method

As mentioned above, a six percent inflation rate and a range of discount rates from six percent to 14% were used. Each individual item was discounted before summing the costs of an option. Prices were subsequently varied on twisted-pair wire and optical fiber to determine the total system's sensitivity to price.

2. Results

In each option, the costs decline as the discount rate rises, which is expected. Option four, the time-phased installation of twisted-pair wire in conduit, produces the lowest costs. Costs for option two, the time-phased installation of optical fiber, are slightly higher than option four's costs. Option one, the immediate installation of optical fiber, generates slightly higher costs while option three's costs are approximately five times higher than the other option's costs (see Figure 5). The costs for options two and four remain approximately parallel as the discount rate grows.

3. Sensitivity

The sensitivity of the system costs to price was tested over seven combinations of price. Twisted-pair wire prices were increased by 25% per test until prices were doubled. Optical fiber prices were decreased by 25% per test

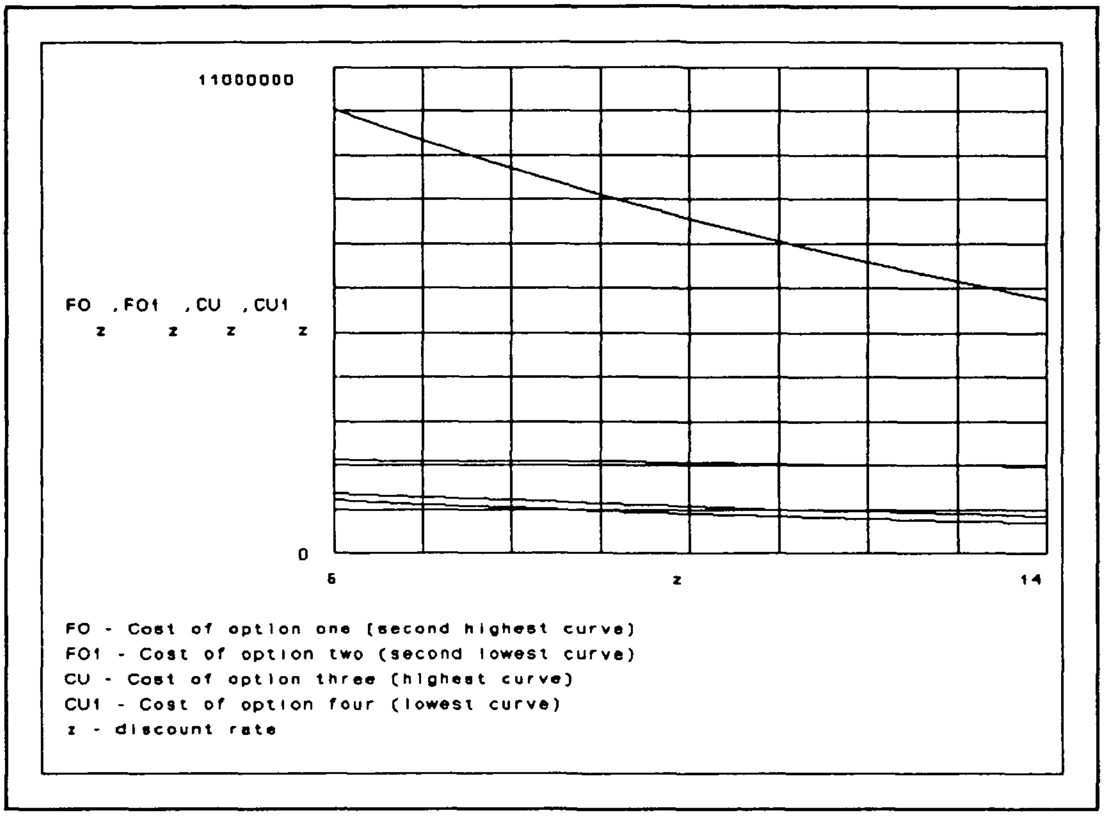

Figure 5 - Cost of Options 1-4 ($millions) versus Discount Rate (percent)

for three tests. Option four costs consistently remained below option two's costs even at the extremes.

4. Installation Costs

A key cost, though not tested, is the installation cost. Installation costs from the Base Communication Plan [Ref 15] show that;

- installation costs in an existing conduit are $2.75/foot,
- trenching costs are $25/foot,
- installing new conduit in an existing trench costs $30/foot and
- trenching across a road costs $45/foot.

These are average costs and costs may differ substantially between rural and urban areas. Installation costs are up to 500 times as expensive as the material costs.

D. Effectiveness Analysis

1. Measures of Effectiveness

An effectiveness analysis was performed for options two and four. The methodology was derived from the TRI-TAC system effectiveness handbook. [Ref. 16] Because only system components were being tested, modifications were made to include measures of effectiveness appropriate to twisted-pair wire and optical fiber. Measures of effectiveness include (in order of weights assigned):

- Performance - the performance of a digital transmission system is one of the most important reasons for replacing an analog network. (Weight = 8)

- Security - security of the communications network is essential. (Weight = 7)

- Maintenance - as an annual cost, it is worthwhile to attempt to reduce maintenance costs where possible. (Weight = 6)

- Size of cable - the capacity of the existing conduit for further expansion determines installation costs and encourages smaller diameter replacement cables. (Weight = 5)

- Electro-magnetic interference/radio frequency interference (EMI/RFI) - EMI/RFI adds to the environmental noise and raises system costs for the added filtering. (Weight = 4)

- Installation - special handling requirements or limitations add to system costs. (Weight = 3)

- Cabling - additional fibers or coverings necessary for stiffening or tensile strength add to system costs. (Weight = 2)

- Environmental factors - the ability to install cables in any area, despite potential hazards, reduces system costs. (Weight = 1)

2. Utilities

Twisted-pair wire and optical fiber were assigned utility scores in each measure of effectiveness based on a prepared scoring chart. The baseline utility was assigned a score of five and deficiencies were subtracted from the baseline while benefits were added to the baseline. Scoring was as follows:

		Option 2	Option 4
1.	<u>Installation</u> restrictions on bending radius = -1 restrictions on stretching = -1 restrictions on crushing = -1	2	4
2.	<u>Cabling</u> extra fibers for stiffening = -1 extra fiber for tensile strength = -1	3	5
3.	<u>Performance</u> average of the following; bit error rate 10^{-8} +/- 10^{-1} = 5 +/- 1 bandwidth 1 GHz +/- 200 MHz = 5 +/- 1 data rate 1 Gbps +/- 200 Mbps = 5 +/- 1 subject to crosstalk = -1	7	1
4.	<u>Environmental factors</u> restrictions on hot areas = -1 restrictions on explosive areas = -1 restrictions on motor/generator areas = -1	4	2
5.	<u>Size of cable</u> given space in conduit for one inch cable, cable with required capacity does not fit = -1	5	4

6.	Maintenance maintenance cost/foot = 10% of price/foot = 5 maintenance cost +/- 2% price/foot = 5 +/- 1	9	5
7.	Security can be tapped = -1 can be tapped without detection = -2	4	3
8.	EMI/RFI subject to EMI/RFI = -1 creates EMI/RFI = -1	5	3

For the hypothetical base used in this thesis, the size of the optical fiber cable became a major factor. In many cases, optical fiber cable would be able to fit into an existing conduit where twisted-pair wire cables of similar capacity would not fit. For security purposes, optical fiber far surpasses twisted-pair wire. Optical fiber does not radiate any emissions that can be used for intelligence collection and it is impossible to tap into fiber and remain undetected. Twisted-pair wire radiates electro-magnetic (E-M) energy and is relatively easy to tap. The large bandwidth of optical fiber also permits the use of elaborate coding schemes to encrypt the transmission. [Ref. 11:p. 11]

Because twisted-pair wire radiates E-M energy, it is a major cause of EMI/RFI. EMI/RFI affects electronic components and also degrades antenna system operation due to the extra noise it adds into the system. Optical fiber transmits photons which do not create EMI/RFI and thus causes no added noise. Twisted-pair wire also acts as an antenna which causes it to couple EMI/RFI. Optical fiber, which is a dielectric, can not couple EMI/RFI.

As noted earlier, optical fiber maintenance costs tend to be ten percent to 20% higher than twisted-pair wire costs. However, as a percentage of purchase price per foot, optical fiber's calculated maintenance cost per foot is lower. The difference in maintenance costs may decline in the future with development of automatic splicers and a more experienced pool of maintenance personnel.

Optical fiber has a substantial edge in many measures of performance. One measure is bit error rate. The bit error rate of twisted-pair wire is on the order of one in ten million (10^{-7}), while optical fiber has a bit error rate of approximately one in one hundred billion (10^{-11}). New communications systems take advantage of the lower bit error rate by reducing the amount of error-checking by the system, thus improving system throughput. Another measure of performance previously mentioned is the maximum data transfer rate. Optical fiber has been demonstrated at data rates up to 20 gigabits/second (Gbps), but is more commonly used below 2.4 Gbps. [Ref. 7:p. 1; Ref. 6:p. 41]

Although both types of media can have similar environmental protection from their coatings, optical fiber, because of its dielectric properties, can be used in some hazardous environments where explosives and explosive fumes may be present.

Installation of optical fiber presents some problems because of its delicate fibers. There are restrictions on bending radius and limits on how far it can be stretched. Twisted-pair wire may be bent back on itself, but also has limits on how far it can be stretched. Both types of media have limits on crushing. To prevent damage to the optical fiber, special fibers are added to the optical cable. Steel strands are added to stiffen the optical cable and also to provide for more tensile strength.

3. Figures of Merit

Figures of merit were calculated for optical fiber and twisted-pair wire by multiplying the weights and utilities assigned to each measure of effectiveness for each option (see Figure 6). The figure of merit for optical fiber is nearly double that of twisted pair wire (see Figure 7). Using the costs calculated in the cost analysis, cost per unit figure of merit is calculated. Option two has a lower cost per unit figure of merit than option four. This is due to optical fiber's superior characteristics in many of the measures of effectiveness.

4. Sensitivity Analysis

A sensitivity analysis was performed using random numbers for weights and utility scores. The results indicate that the weights assigned to the measures of effectiveness had little effect on the figure of merit in the five tests performed. The tests performed on the assigned utility scores

Measures of Effectiveness	W_i := (weights)	$U_{i,1}$:= (optical fiber)	$U_{i,2}$:= (twisted-pair)
size of cable	5	5	4
security	7	4	3
EMI/RFI	4	5	3
maintenance	6	9	5
performance	8	7	1
environmental factors	9	4	2
installation	3	2	4
cabling	2	3	5

Figure 6 - Weights and Utilities for Measures of Effectiveness

demonstrated greater impact on the figures of merit.

Break-even optical fiber figures of merit were calculated by using the calculated costs for both optical fiber and twisted-pair wire and the twisted-pair figure of merit (see Figure 8). Below the break-even figure of merit, twisted-pair wire had the lower cost per unit figure of merit. Above the break-even figure of merit, optical fiber had the lower cost per unit figure of merit. The break-even optical figures of merit were indexed by discount rate with higher discount rates needing higher figures of merit. For optical fiber to be cost-effective, the optical fiber figure of merit must be greater than the break-even figure of merit for the discount rate used.

FOM = figure of merit

$$FOM_j := \frac{\sum_i \left[w_i \cdot u_{i,j} \right]}{\sum_i w_i}$$

$$FOM_j = \begin{bmatrix} 5.528 \\ 3.184 \end{bmatrix}$$

Figure 7 - Figure of Merit

5. Results

The cost-effectiveness analysis indicates that despite higher system costs, the superior characteristics of optical fiber make it the cost-effective choice. The weights and utilities assigned and the measures of effectiveness selected are subjective and not all-inclusive. Those areas that are important to the decision-makers should be included in the measures of effectiveness and weighted accordingly. The TRI-TAC methodology is very effective in identifying areas of particular importance to communications systems.

FOM_z = breakeven figure of merit

$$FOM_z := \frac{Cost_{FO1_z} \cdot FOM_2}{Cost_{CU1_z}}$$

FOM_z
3.644
3.681
3.718
3.754
3.789
3.823
3.857
3.891
3.924

FO1 - option two
CU1 - option four

Figure 8 - Break-even Figure of Merit

V. CONCLUSIONS

In this thesis, four options, involving twisted-pair wire and optical fiber, have been presented for the BITS backbone cable plant. After making assumptions about the fictitious base, its existing backbone cable plant, and the behavior of the component costs, each of the replacement options was evaluated in light of current and future communications requirements. In the cost analysis, the time-phased installation of twisted-pair wire in existing conduit demonstrated the lowest costs. However, as was shown in the effectiveness analysis, the time-phased installation of optical fiber produced a higher figure of merit and a lower cost per unit figure of merit. Optical fiber is cost-effective because it is superior to twisted-pair wire in nearly all areas of comparison. In the areas where optical fiber lags behind twisted-pair wire, progress is being made to correct the deficiencies. It is clearly the transmission medium of choice in the civilian sector.

A. IMPLICATIONS

What can be learned from this thesis beyond the head-to-head comparison of optical fiber and twisted-pair wire? Two areas are of immediate importance:

- Unless the applications exist that require the bandwidth of optical fiber, fiber may not be justified.

- Installation costs are a more important factor than material costs.

Applications, like interconnection of high-speed LANs and video teleconferencing, will drive the adoption of optical fiber. If all that is required is simple voice traffic and interconnection of low-speed LANs, then twisted-pair wire will provide more than adequate capacity and capability. However, the future appears to demand ever higher data rates. Desk-top equipment may require more than 100 megabits/second. The pierside connections may easily exceed one gigabit/second. What can be expected is that users will find a use for any excess capacity.

It is apparent that labor costs are not substantially higher to install excess system capacity when space is available in the conduit or the trench is open. In cases where the conduit is nearly full, the small size of optical fiber cables make it a superior choice. Excess capacity is relatively easy to provide using optical fiber because of the large bandwidth available and the small size of optical fiber cable.

B. THE FUTURE

Beyond the choice of physical transmission media, the topology used in this thesis may be inadequate in the future. At this time, the data rates on optical fiber-based broadband networks are limited by the speed of the switch. As noted earlier, photons must be converted back into electrons to pass through the switch. Development of an optical switch is in progress and looks promising. This topology is still limited by the capacity of the switch. A completely new topology may be required to meet the demands for a system whose capacity is even greater and is not subject to single point failure like a PABX system.

Currently, LANs, like the fiber distributed data interface (FDDI), offer extremely high data rates and protection against a single point failure. However, FDDI and other LANs, can not provide time-critical services, like voice and video, efficiently. The successor to FDDI, FDDI II, may be able to transfer voice and video successfully. Both FDDI and FDDI II require optical fiber to provide the high data rates required. Optical fiber installed for an ISDN PABX network, if properly designed, could be converted to the FDDI topology for little additional cost.

Optical fiber is the physical transmission medium of today. Local telephone and cable television companies are rapidly installing it in the local loop. Most of the long-distance networks have already been converted. Its benefits are well-known and its liabilities are being reduced. By converting to optical fiber where appropriate, the Navy positions itself for the future.

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